

VII. ENERGY DOUBLER MAGNET POWER SUPPLY AND QUENCH PROTECTION⁽¹⁾

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I. Introduction

The Energy Doubler magnet system consists of a series circuit of 774 dipoles and 240 quadrupoles distributed around a ring of 1-km radius. This magnet must be repetitively excited from 500 amps (.5T) to 4000 amps (4T) as often as 5000 times daily. Since the amount of stored electrical energy, 300 MJ, is significant, it is necessary that it be transferred back to the power grid when the magnet is de-excited.

Another consequence of the pulsed operation is the generation of heat in the superconductor by eddy current losses. This heat load at liquid helium temperatures must be tolerable and this imposes requirements reflected in the magnet design by the choice of a cable with a limited amount of copper matrix. However, quenches, when they occur, do not recover in this cable and a mechanism for removing stored energy from quenched magnets is required.

The kinetic energy of the proton beam circulating within the magnets may be as large as 10 MJ, and because it is inevitable that some of this beam will strike the magnets from time to time, initiating quenches, safe and reliable quench-detection and protection schemes are required.

II. Power Supply

The main power circuit is illustrated in Fig. 1, and parameters of the power supply are given in Table I. All of the magnet coils are connected in series on the "coil bus" and the current returns through the "return bus." As the return bus contributes to the magnetic field

in the Energy Doubler magnet design, it is necessary that it carry current.

Six ± 2 -kV, 4500-amp, bi-directional converter-inverter energy-transfer supplies are distributed with equal spacing along the coil bus. These six power supplies are obtained by converting twelve existing Main Ring power supplies to Energy Doubler use. At each of the A1, B1, C1, D1, E1, and F1 service buildings, the two 1-kV Main Ring bend bus power supplies would be removed from the Main Ring magnet system and would be connected in series to provide a 2-kV energy transfer station for the Doubler. These power supplies will have a local voltage regulation loop. The Main Ring bus would bypass these buildings with a minor modification to the bend busses in the tunnel. A schematic of a typical power supply is shown in Fig. 2.

In addition, there is one low-voltage holding supply which is capable of continuous operation at 4500 amps. This power supply must be constructed anew and requires a special transformer providing a lower voltage than existing Main Ring transformers but capable of continuous operation at 4500 A. This power supply will act as the system current regulator.

It is the function of the energy-transfer supply to rapidly change the current of the magnet, while the holding supply is used to make up non-superconductor bus losses during constant current portions of the cycle. All six of the energy-transfer supplies will be programmed to produce equal voltages. Thus, the maximum voltage between the coil and ground, or between the coil and bus, will be one-half of the peak voltage of each supply or a maximum of 1 kV.

Table I

Energy Doubler Power Supply

No. of Rectifier Stations (Energy Transfer)	6	
No. of Rectifier Stations (Holding)	1	
Peak Current	4500	amps
Maximum rms Current (Energy Transfer)	2500	amps
Maximum rms Current (Holding)	4500	amps
Peak Power (Energy Transfer)	45	MW
Peak Power (Holding)	655	kW
Peak Voltage (Energy Transfer)	10	kV
Peak Voltage (Holding)	150	V
Peak Voltage to Ground	1000	V
Peak Coil to Bus Voltage	1000	V

Current Data - Magnets

Dipole Inductance	0.04	H
Quadrupole Inductance	0.006	H
Total Inductance (100 cells)	33.0	H
Total Resistance of Cables and Holding Supply Components	0.024	ohm
System L/R	1375	sec

Nominal Excitation Profile

Maximum Rate of Rise	303	amps/sec
Injection Current	500	amps
Flattop Current	4000	amps
Time to Flattop (Minimum)	9.9	sec
Maximum Rate of Fall	-303	amps/sec
Energy Transfer Station Ripple	1	volt peak
Holding Station Ripple	0.1	volt peak

Current Tolerance

Energy Transfer Mode	N.A. (voltage regulated)	
Holding Mode	±40	mA

Emergency Energy Dump

Number of Stations	6	
Resistance/Station	0.5	ohm
Peak Voltage to Ground During Dump	1000	V
Peak Coil to Bus Voltage During Dump	1000	V
Total System L/R in Dump Mode	11	sec

The maximum performance cycle is shown in Fig. 3. At the start of the cycle, the current is held constant at 500 amps while 100-GeV protons are injected from the Main Ring. The energy-transfer stations then increase the magnet current and the beam is accelerated. When the peak current is reached, the energy-transfer stations are removed from the magnet circuit and the current is held constant by the current-regulated holding supply. A current tolerance of ± 40 mA is required while the beam is slowly extracted from the synchrotron and sent to users in remote locations. The close tolerance on magnet current is set by the requirements of the beam-extraction process.

Removal of the energy-transfer stations is accomplished by bringing the power-supply voltage to 0 V and shorting its output with bypass SCR's. A schematic of the energy-transfer station is shown in Fig. 4. In order to keep the dc losses to be supplied by the holding supply to a minimum, the bypass SCR's must be installed in the accelerator tunnel or substantial copper busses must be provided between the tunnel and service buildings at the six power-supply locations. This heavy copper bus is essential at the location of the holding supply (A1).

III. Quench Detection

For detection of quenches, we have developed a Z80 microprocessor system which sequentially measures the voltage across each half-cell of magnets (4 dipoles and one quadrupole). One microprocessor system, shown in Fig. 5, monitors 169 magnets or 1/6 of the entire accelerator.

Each system runs under the supervision of a high-level interpretive BASIC language program. This program is responsible for setting up parameters, analyzing statistics, reporting status and in general, communicating with the operator, either directly or via a link with a central computer.

Every 10 msec, this supervising program is interrupted for a high-priority safety scan of all the analog signals from its 1/6 of the accelerator. An auxiliary arithmetic processor is used to enhance the fast on-line safety analysis. If the scan does not reveal any anomalies, the software generates a "heartbeat." If an anomalous condition - quench, overvoltage, lead runaway, overcurrent, etc. - is detected or if the processor fails to give an indication of activity to the heartbeat detector, the emergency dump system, described below, is activated. The 10 msec between these scans is negligible in comparison to quench development

times. However, good voltage detection sensitivity is critical to insure adequate detection.

The quench-detection algorithm depends on the fact that voltages tapped from the magnets should be distributed according to known inductances. A deviation of a few tenths of a resistive volt indicates the start of a quench.

IV. Quench Protection

When a quench is detected, the power supply is turned off and a 0.5 ohm air-cooled "energy fountain" resistor is switched into the coil bus at each of the energy-transfer stations by the emergency dump switch shown in Fig. 4. This causes the magnet current to decay with a time constant of 11 seconds.

In Fig. 6, we show the electrical connection of four protection units, each containing four dipoles and one quadrupole, a half-cell of the accelerator. After the resistors have been switched into the coil bus, a pulse train is applied to the gates of the shunt thyristors all around the magnet ring. If resistive voltage has developed across any protection unit, the associated shunt thyristor will turn on and divert the decaying current around the quenched unit, through two safety leads. These leads are essentially 3/8 inch diameter copper rods designed to carry one pulse of decaying current without damage and to cause a negligible heat leak when passive. They will, of course, have to cool down again before re-use.

In order to protect the thyristors against damage from radiation, they are mounted in a "hole-in-the-wall" module which extends 4 feet through the wall of the tunnel housing the synchrotron. Surrounding earth provides the shielding. Nevertheless, all shunt thyristors will be regularly tested by gating them on and ramping the magnets fast enough to force current into them. The microprocessor system will scan voltage taps for any open thyristors.

The return bus will be protected by a resistive dump connected across the fold-point of the bus. Portions of the busses linking longer spans between magnets will be made of fully-stabilized superconductor.

Since the quenched magnets in a protection unit are shorted, they must absorb all their stored electrical energy without damage. To prevent damage, the normal zone must propagate rapidly in the quenched magnet, causing the current to be rapidly shunted out of that unit. To speed the propagation of the quench, we have installed a thin stainless-steel heater strip adjacent to the coil in two high-field regions of the magnet. If a quench is detected, then heaters in all the dipoles of the quenched unit will be fired.

V. Power Supply Controls

The Energy Doubler power supply is a system which provides the prescribed magnet program as defined by the smallest set of parameters necessary. Interaction with the main control system is very small in contrast to the present Main Ring power supply. A small mini-computer or micro-computer will be an integral part of the power supply system. The main control system will communicate a few essential commands and parameters over a slow serial link to the power supply describing the required ramp. The power-supply computer will generate the power-supply voltage and current curves for the power supplies from the ramp parameters, the accelerator clock, and the known parameters of the power supplies and load. It is expected that curve increments will be issued on the order of every 10 ms by the power-supply computer.

Since the Energy Doubler is a temperature-regulated load and the field vs current transfer function is well known and stable without remanent field and saturation fluctuations, the magnet current strictly defines the field. Hence, no independent field information is required for regulation; only accurate and stable reference levels and curves and current readouts provided by a high-quality transducer are required. These are all integral parts of the regulation hardware not requiring real-time interaction with a computer to effect regulation.

If, contrary to our present expectations, feed-forward or learning techniques are required, these functions will be performed by the power supply computer if global in nature, or by individual processors at each of the stations, if local in nature. Readout of the magnet current via some channel of the main control system is, of course, essential to check that the power supply is performing as commanded.

The quantity of information which must pass between the main control system and the quench-detection monitors is extremely small and keyed to human-response timing. This communication should be in English so that a human can make sense of it as it is happening. The power supply end of this communication will be handled by a supervisory program written in BASIC language as previously mentioned. The transmission can be easily and effectively handled by an RS-232C serial link operating at some moderate baud rate, i.e., 2400-4800 baud, over a simple shielded twisted-pair cable.

A few dedicated high-quality, i.e., 3/8" Andrew Heliax, cables circling the Main Ring with access at the six power-supply stations will be required for interconnecting the power supply system. These can be part of the nineteen-circuit cable presently being installed, or separate additional cables placed in the tunnel cable trays.

VI. Tests

We have made tests to check the performance of both the quench-detection and the quench-protection schemes described above. To measure the efficiency of the heaters and to study the growth of quenches, we used a single shorted Energy Doubler dipole magnet. By pulsing a small heater resistor and measuring the fusing current,

$$M = \int_{t_q}^{\infty} I^2 dt \quad ,$$

following the quench we established the curve of Fig. 7 showing the maximum temperature attained. This temperature occurs at the place where the quench started and is a known function of the fusing current. The temperature reaches a dangerous value for quenches which start when the magnet is near its peak current and it is clear that a quench in a single magnet of the five-magnet protection unit would be destructive. Figure 7 also shows the effect of firing the heaters to speed the propagation of the quench. Heaters provide adequate protection at all excitations if the quench detection scheme is sufficiently sensitive to detect the quench before excessive energy has been dissipated in the local quench. The prototype magnet voltage tap measurement technique using voltage dividers to ground is marginal. Another

technique measuring the protection unit voltage differentially is under development. This technique promises to improve the sensitivity by approximately one order of magnitude.

Tests have also been made on a string of four dipoles up to a current of 2500 amps, which show the results indicated in Fig. 5 to be valid for protection units. Measurements above 2500 amps were not possible because the pressure rise in the liquid-helium cryostat could not be supported by the mechanical structure of the string. The magnets will soon be replaced by elements with strengthened cryostats and a lower volume of trapped helium which should overcome this difficulty.

The string was also used to check a prototype of the quench-detection system in a fairly realistic environment. This system performed well even when resistive thresholds as low as 5 volts were set, no difficulties due to noise or transients confusing the safety scan algorithm were experienced. In addition, the threshold voltage for the detection of lead runaway was set at 50 mV without false detection.

The present string has been repeatedly ramped between 500 amps and 2000 amps, which represents the top energy of the Fermilab conventional accelerator (500 GeV). Figure 8. shows the voltages and currents in the string for this "Energy Saver Mode."

- (1) This chapter is a restatement and modification of a paper entitled "A Superconducting Synchrotron Power Supply and Quench Protection Scheme" by R. Stiening, R. Flora, R. Lauckner, and G. Tool; presented at the 1978 Applied Superconductivity Conference.

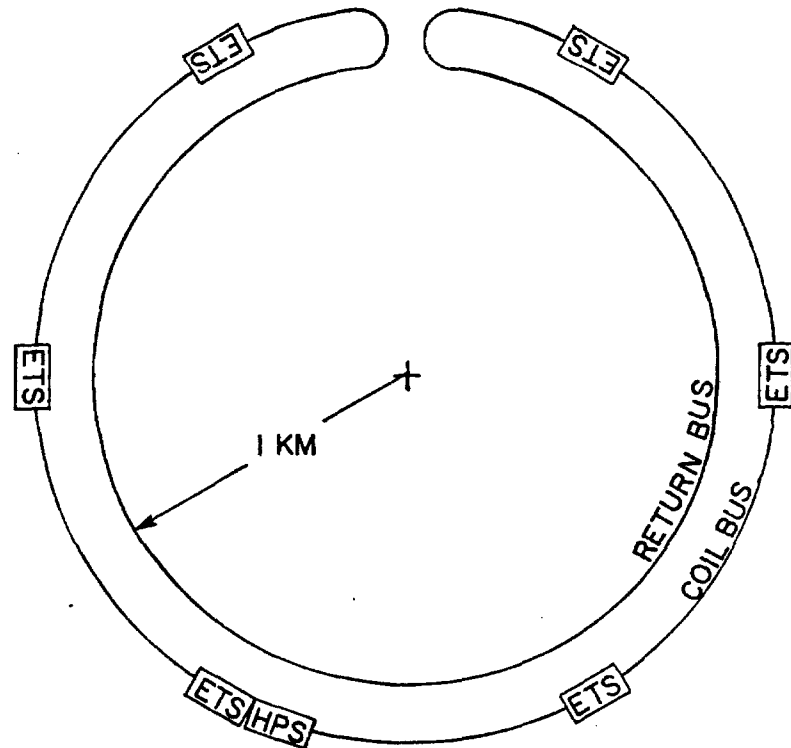


Fig. 1. The main power circuit for the Energy Doubler. When constant magnet current is required, the energy-transfer supplies are switched out of the circuit and the holding supply makes up for non-superconducting bus losses.

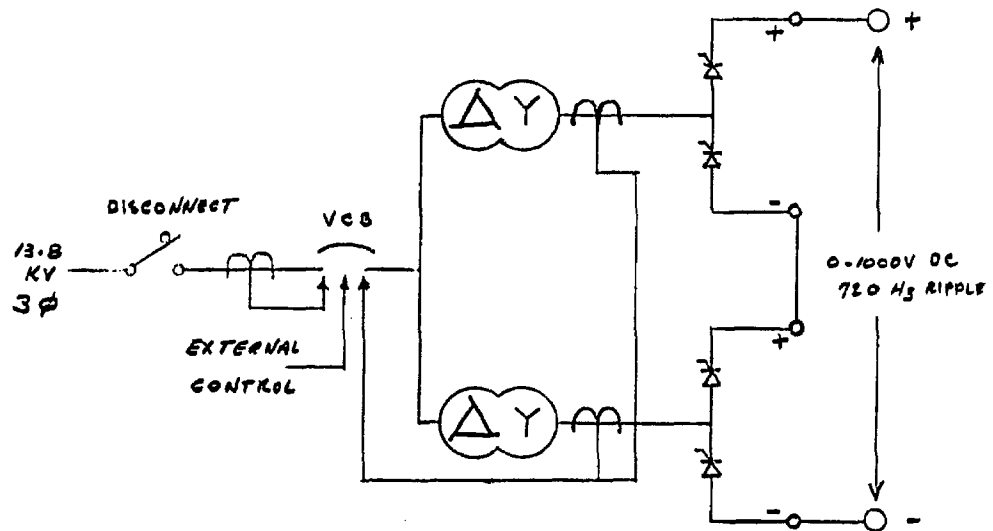


Fig. 2. Schematic of typical power-supply unit ac and rectifier circuits.

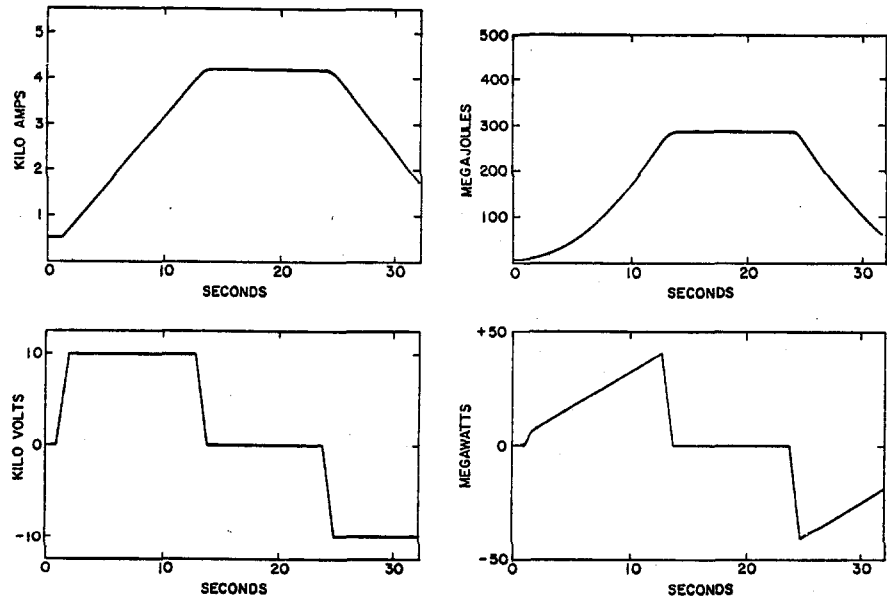


Fig. 3. Maximum performance magnet cycle.

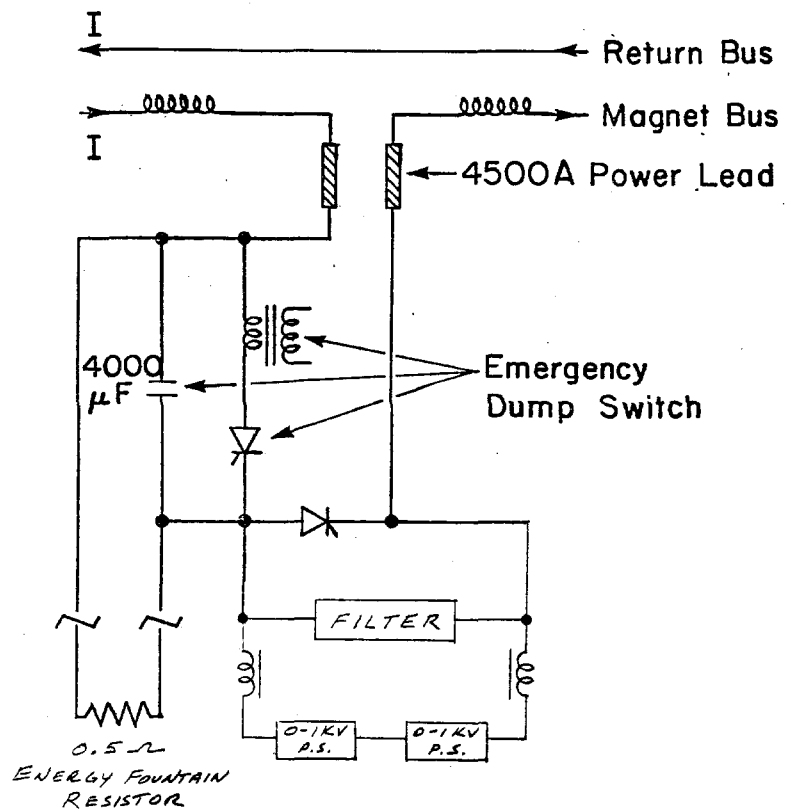


Fig. 4. Energy-transfer station.

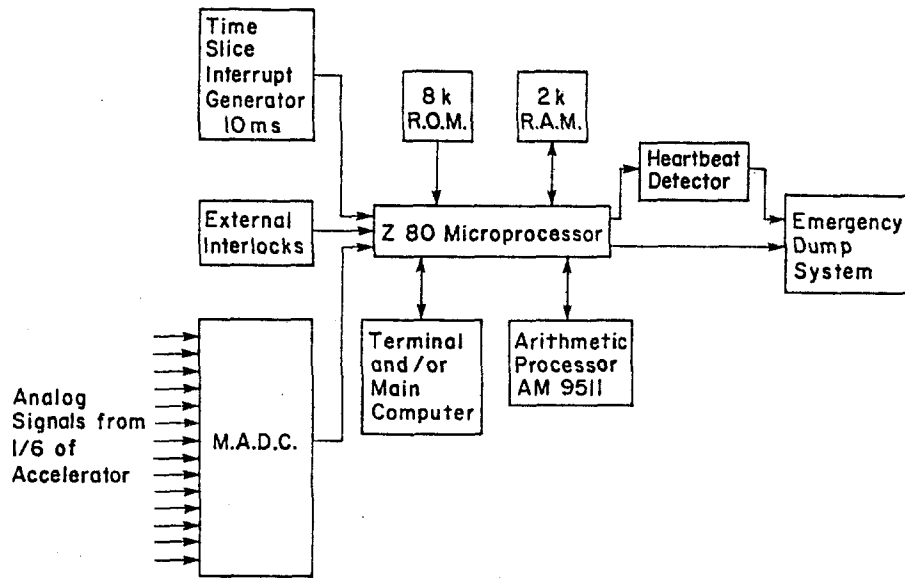


Fig. 5. Quench-protection microprocessor system. Six of these will be required to scan the entire superconducting-magnet system every 10 msec.

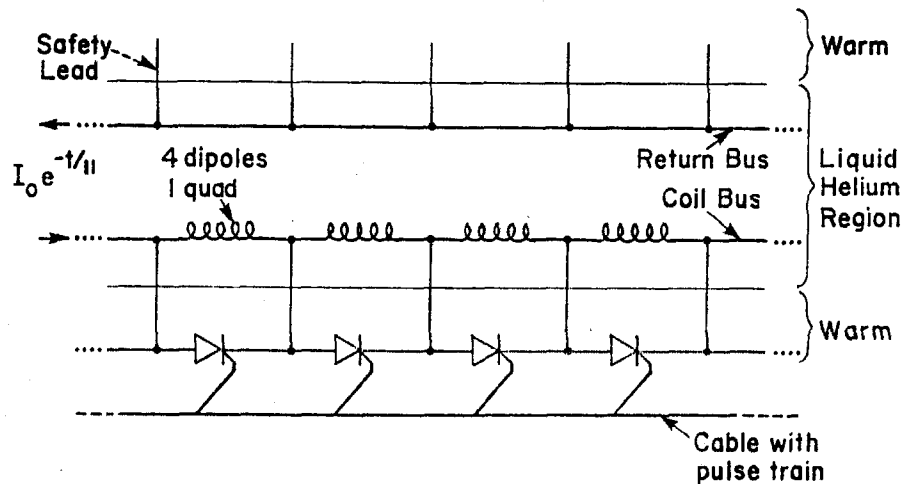


Fig. 6. Four adjacent magnet-protection units. Each is one half-cell of the accelerator. Decaying current is shunted out of a quenched magnet through safety leads and thyristor.

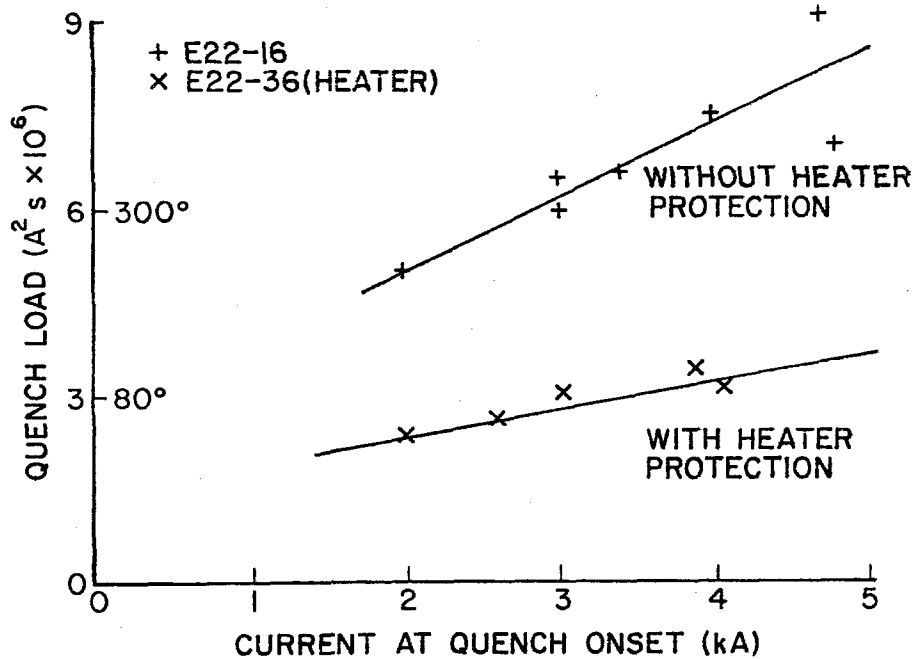


Fig. 7. The maximum temperature reached in a quenched, shorted, Energy Doubler magnet. These results indicate that a single shorted magnet may damage itself unless protection heaters are pulsed to speed propagation of the quench through the magnet.

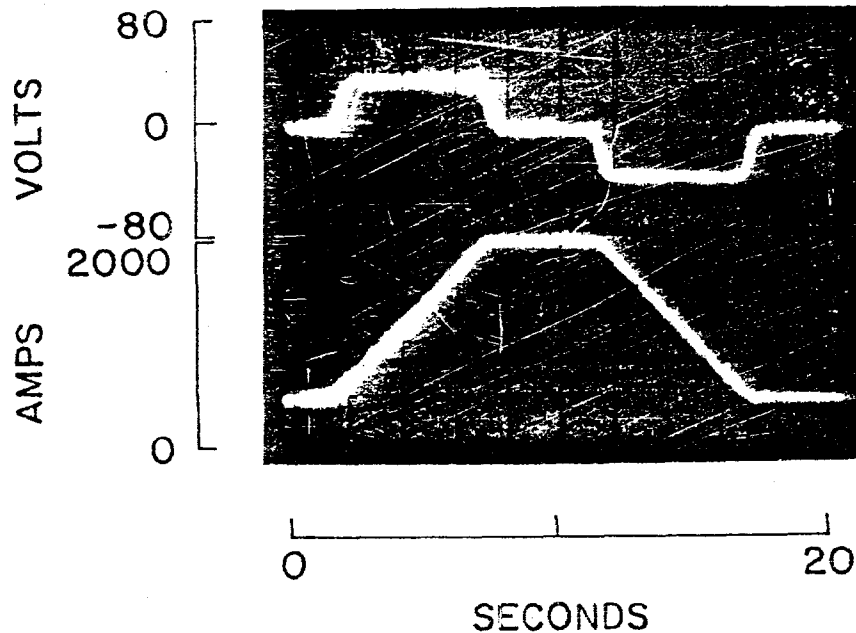


Fig. 8. Voltage (above) and current traces from the four-magnet string being ramped in the "Energy Saver Mode" 100-500 GeV. This is equivalent to the top energy of the present Main Ring.